Searching for Sub-Gev Dark Matter at Fixed Target Neutrino Experiments

Patrick deNiverville

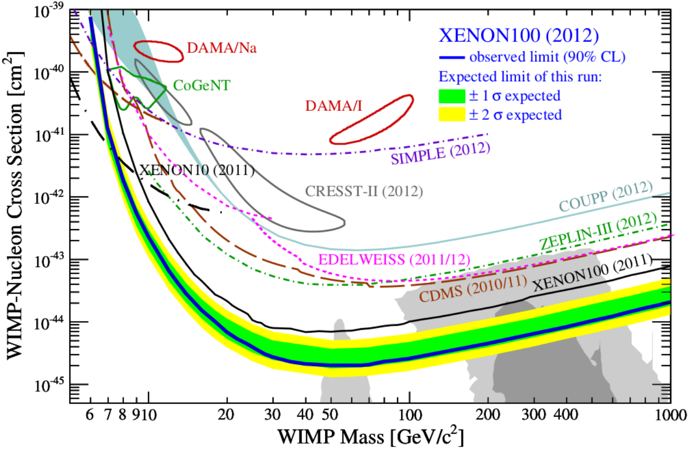
University of Victoria

TAUP2013

[P. deNiverville, D. McKeen & A. Ritz '12, arXiv: 1205.3499 [hep-ph]]

Motivation

Experimental limits for WIMP-Nucleon cross section



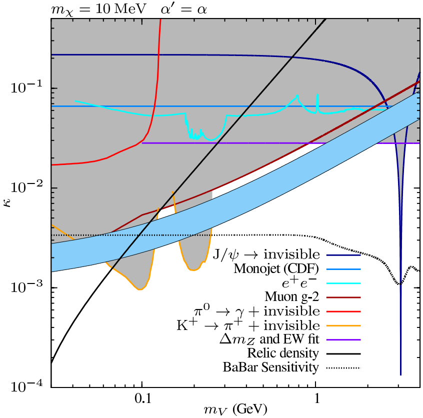
[XENON Collaboration 2012, arXiv:1207.5988 [astro-ph]]

A Low Mass Dark Matter Scenario

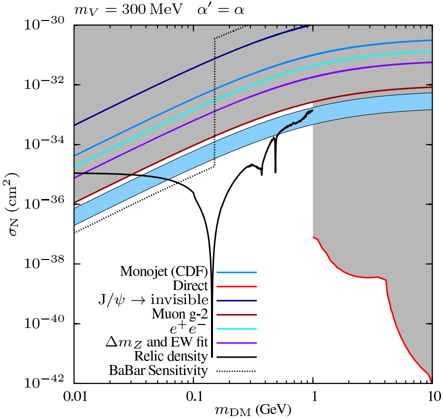
$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F_{\mu\nu} + |(\partial_\mu - e' V_\mu)\chi|^2 - m_\chi^2|\chi|^2 + \mathcal{L}_{h'}$$

- V can be produced through kinetic mixing with γ at $\mathcal{O}(\kappa^2)$.
- χ serves as Dark Matter candidate, couples to SM through the V.
  - $2m_\chi < m_V$ for production in V-decay, keep V lifetime short.
- The $U(1)'$ coupling strength α' must be kept small to maintain perturbativity.
  - We set $\alpha' \sim \alpha_{\mathrm{em}}$, but could be varied quite widely.
- Requiring that $\Omega_\chi \sim \Omega_{\mathrm{matter}}$ relates κ, α', m_χ and m_V [Pospelov, AR & Voloshin '07] .

Scenario Parameter Space

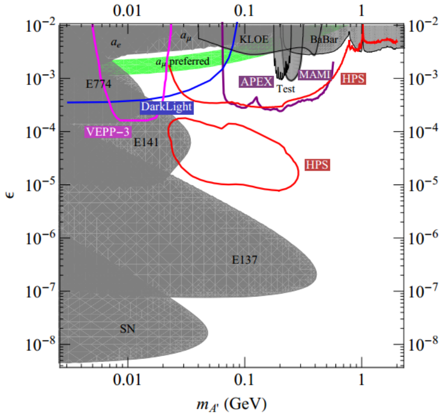


Dark Force Parameter Space

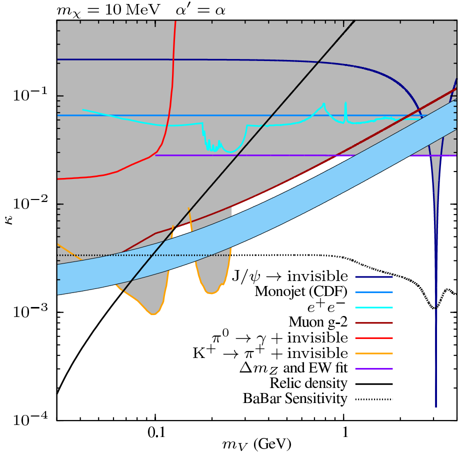


Direct Detection Parameter Space

Dark Force Parameter Space

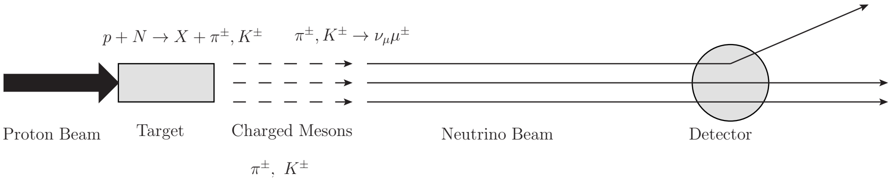


The standard dark force limit plot, $m_V < 2m_\chi$ [Intensity Frontier Workshop, Hewett, Werts et al '12]



Adapted for a dark matter scenario with $m_V > 2m_\chi$, short lived V and $BR(V \to \mathrm{DM}) \sim 1$.

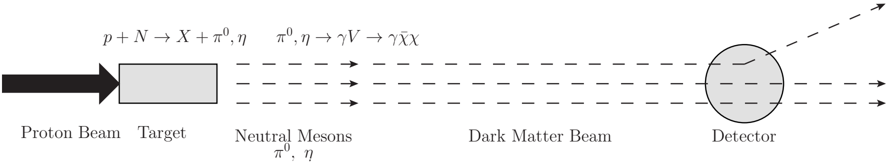
Fixed Target Neutrino Experiments

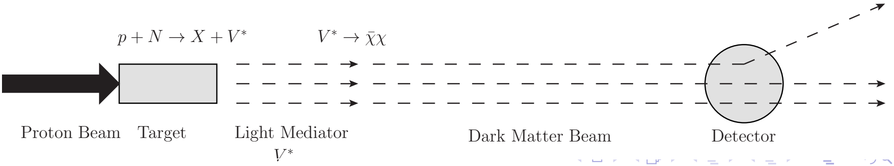


- Experiments involve impacting a target with $\sim 10^{20} - 10^{22}$ protons to produce a high intensity neutrino beam.
  - Neutrinos produced from decays of charged mesons.
  - Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.
- Non-neutrinos are removed from the beam before it reaches the target to reduce background.
- Several fixed target neutrino experiments were investigated: LSND, MiniBooNE, T2K, MINOS.

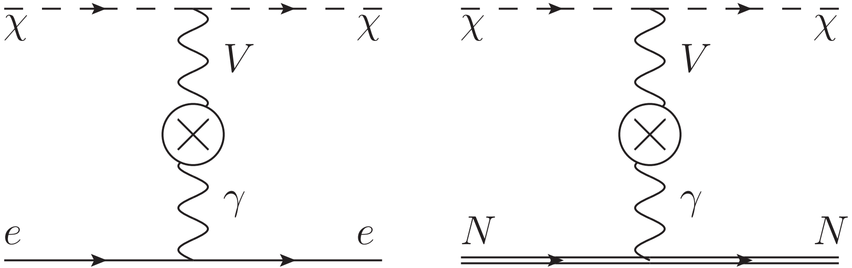
Dark Matter Beams

- Fixed target neutrino experiments could also produce large numbers of light, hidden sector particles.
- So long as they are long-lived and neutral under SM gauge groups they could reach the neutrino detector, too.
  - Results in the production of a dark matter beam alongside the neutrino beam.
- Examined two production methods: neutral meson decay and direct parton-level production.



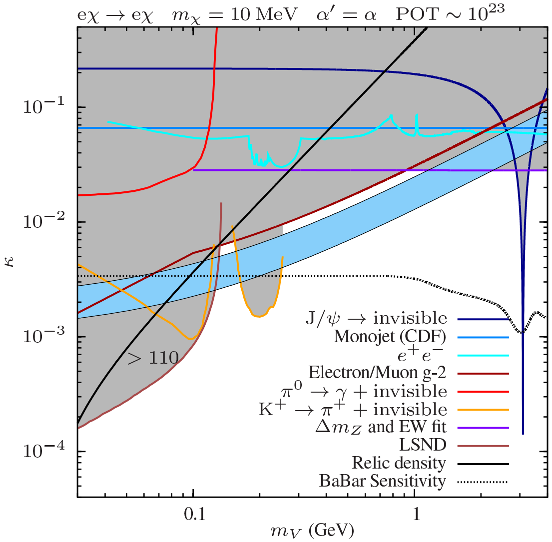


Detecting Dark Matter with Neutrino Detectors



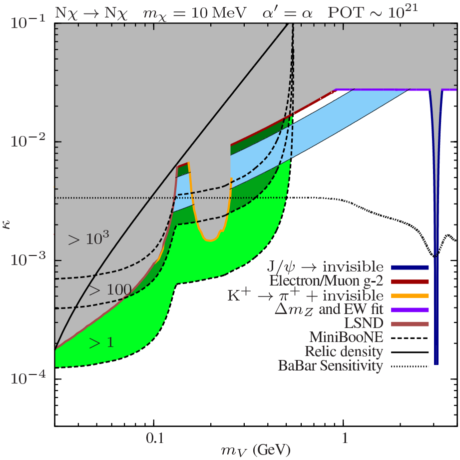
- In the most straightforward analyses, without special timing or energy cuts, dark matter signal manifests as neutral-current-like elastic scattering events in excess of those expected from neutrinos.
  - For our analyses, neutrino events are the background. Need to generate a significant number of excess events to obtain useful sensitivity.
- Interaction channel chosen for analysis of each experiment dependent on backgrounds and the neutral-current elastic scattering analyses published.

LSND

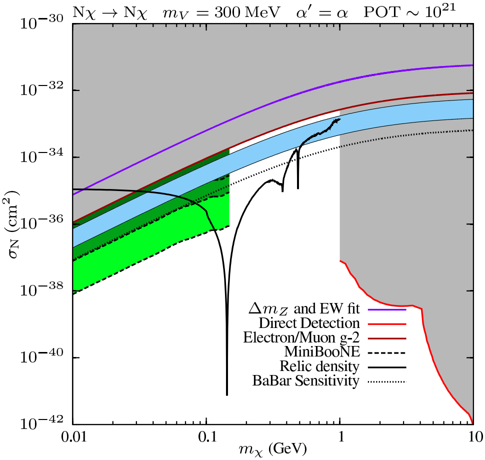


[Batell'09, deNiverville'11]

MiniBooNE

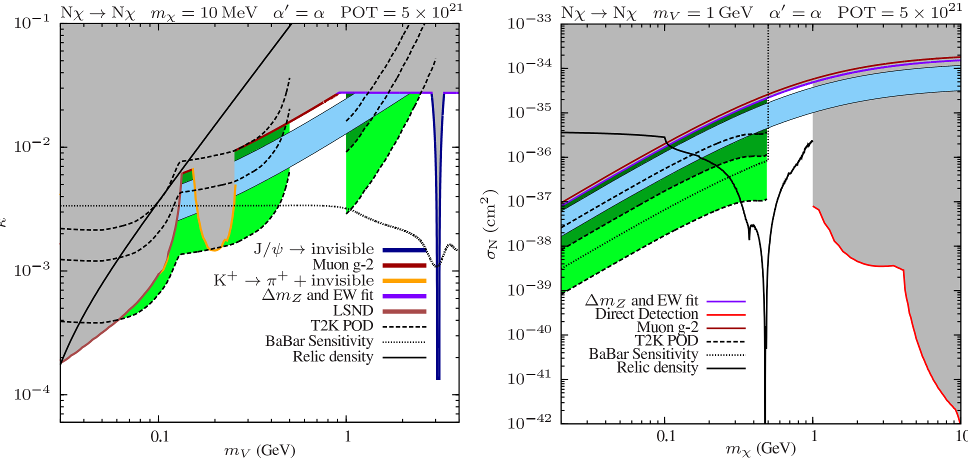


$N\chi \to N\chi \quad m_\chi = 10$ MeV $\quad \alpha' = \alpha \quad$ POT $\sim 10^{21}$
κ
m_V (GeV)
$> 10^3$
> 100
> 1
$J/\psi \to$ invisible
Electron/Muon g-2
$K^+ \to \pi^+ +$ invisible
Δm_Z and EW fit
LSND
MiniBooNE
Relic density
BaBar Sensitivity



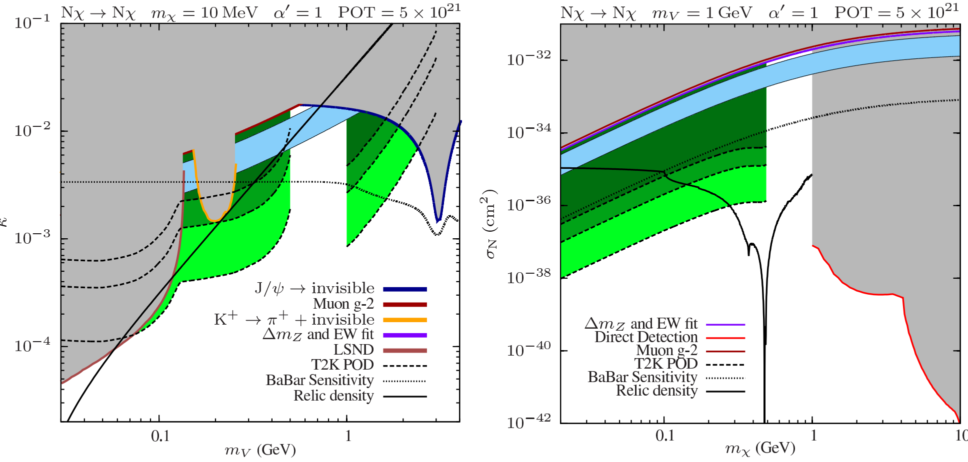
$N\chi \to N\chi \quad m_V = 300$ MeV $\quad \alpha' = \alpha \quad$ POT $\sim 10^{21}$
σ_N (cm^2)
m_χ (GeV)
Δm_Z and EW fit
Direct Detection
Electron/Muon g-2
MiniBooNE
Relic density
BaBar Sensitivity

T2K - POD



Nχ → Nχ $m_\chi = 10$ MeV $\alpha' = \alpha$ POT $= 5 \times 10^{21}$
J/ψ → invisible
Muon g-2
$K^+ \to \pi^+ +$ invisible
Δm_Z and EW fit
LSND
T2K POD
BaBar Sensitivity
Relic density
m_V (GeV)
κ
Nχ → Nχ $m_V = 1$ GeV $\alpha' = \alpha$ POT $= 5 \times 10^{21}$
Δm_Z and EW fit
Direct Detection
Muon g-2
T2K POD
BaBar Sensitivity
Relic density
m_χ (GeV)
σ_N (cm^2)

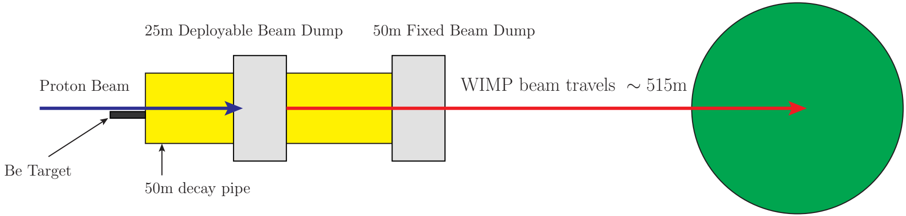
T2K - POD



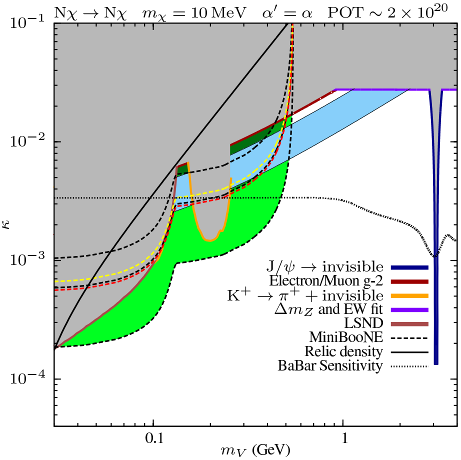
$N\chi \to N\chi$ $m_\chi = 10$ MeV $\alpha' = 1$ POT $= 5 \times 10^{21}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
κ
0.1
1
m_V (GeV)
$J/\psi \to$ invisible
Muon g-2
$K^+ \to \pi^+ +$ invisible
Δm_Z and EW fit
LSND
T2K POD
BaBar Sensitivity
Relic density
$N\chi \to N\chi$ $m_V = 1$ GeV $\alpha' = 1$ POT $= 5 \times 10^{21}$
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
σ_N (cm^2)
0.1
1
10
m_χ (GeV)
Δm_Z and EW fit
Direct Detection
Muon g-2
T2K POD
BaBar Sensitivity
Relic density

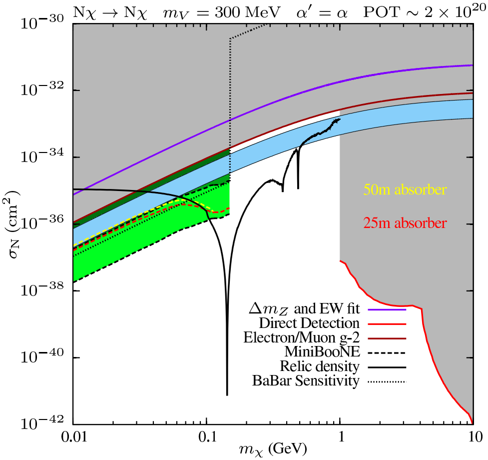
Reducing the Neutrino Background

- Sensitivity can be improved by either reducing the number of neutrinos reaching the detector, or by differentiating between likely neutrino and dark matter events.
  - Timing Cuts - DM beam takes longer to reach the detector than neutrino beam.
  - Energy Cuts - DM energy distribution peaks at a higher energy than the neutrino distribution.
- Target-off/Beam Dump runs
  - Can dramatically decrease the neutrino flux by sending a proton beam directly into the beam dump, while leaving DM flux largely unchanged.
  - Proposal submitted for extra 2×10^{20} POT off-target run at MiniBooNE. [arXiv:1211.2258v1, with Richard Van de Water] .



MiniBooNE Proposal





Conclusion

- Thermal relic WIMP with a sub-GeV mass and interactions mediated by a light U(1)$'$ vector boson provides a viable dark matter candidate.
- This candidate escapes many of the best limits imposed by direct, indirect and collider searches.
- Fixed Target Neutrino Facilities possess sensitivity to these hidden-sector scenarios.
  - Capable of probing regions of the hidden-sector parameter space currently inaccessible to other techniques while using a straightforward counting approach.
  - MiniBooNE can provide great limits on V masses below m_η.
  - T2K provides sensitivity at $\mathcal{O}(1\mathrm{GeV})$.
- Running a Fixed Target Neutrino Experiment in an off target mode could provide new sensitivity, while requiring far fewer POT
- Backgrounds in all cases can be further reduced by introducing timing and energy cuts.
  - Experiments with far detectors, such as T2K with Super-K, may be able to completely seperate dark matter events from neutrino events using timing cuts.

Backup Slides

Choosing a Portal

There is a limited set of low dimension (relevant or marginal) operators which can be used to write the interactions between a neutral hidden sector and the Standard Model:

- Vector Portal: A new U(1)$'$ vector (V) kinetically mixed with hypercharge. $\mathcal{O}_4 = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu}$.
- Higgs Portal: A scalar sector (S) coupled to the Higgs. $\mathcal{O}_4 = \Lambda_S S^2 H^\dagger H$
- Neutrino Portal: A set of Right-Handed neutrino-like Majorana fermions. $\mathcal{O}_4 = Y_N^{ij} \bar{L}_L^i H N^j$

While all three can produce dark matter candidates we will focus our attention on the bilinear interactions of the Vector and Higgs Portals.

Choosing a Portal

For $m_V > 2m_\chi$

- **U(1)$'$ Mediator - Vector Portal**
  - **Fermionic DM** - s-wave annihilation and an increased dark matter number density due to the low dark matter mass results in a visible distortion of the CMB. Also leads to a more visible signal from galactic center. [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08]
  - **Scalar DM** - p-wave annihilation allows this scenario to be viable for small κ, as the annihilation rate is suppressed by an additional factor of v. A small v heavily suppresses the dark matter annihilation rate.
- **Scalar Mediator - Higgs Portal**
  - **Scalar DM** - s-wave annihilation excludes this scenario for the reasons given previously.
  - **Fermionic DM** - p-wave annihilation renders this model viable. However, fermionic DM requires a large mixing, which could affect B decays. [Bird, Kowalewski & Pospelov 2006]

Experimental Constraints

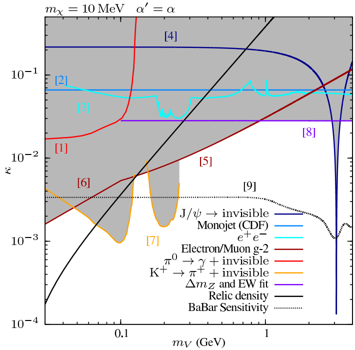
Cosmological:

- Big Bang Nucleosynthesis - So long as $m_{\mathrm{DM}} > 1-2$ MeV, freeze-out occurs before BBN [Serpico & Raffelt '04, Jedamzik & Pospelov '09] .
- Cosmic Microwave Background - Annihilation through p-wave, has little effect [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08] .

Particle Physics:

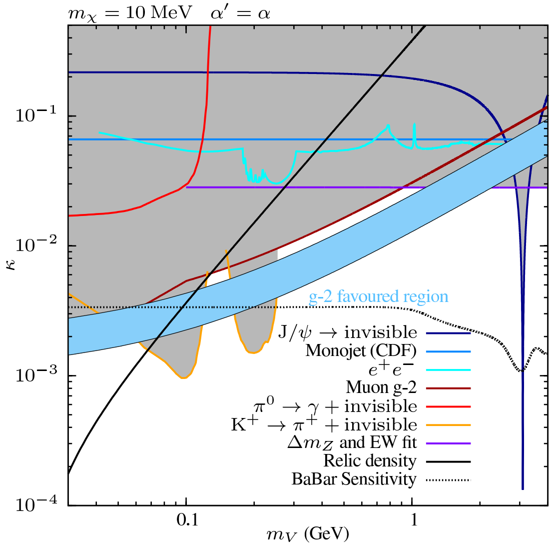
- Electron and muon $g-2$ - Affects the value of $g-2$. Quite strong at low mass, but weakens with increasing mass [Fayet; Pospelov '08;] .
  - Can also bring theoretical value of muon $g-2$ into closer agreement with experimental value.
- $V \to l^+ l^-$ - Weak so long as $BR(V \to 2\chi) \sim 1$, holds for most of parameter space of interest. [Bjorken et al. '09; Batell et al '09; Reece & Wang '09; MAMI '11, APEX '11, BaBar'12, ...]
- Missing energy in rare decays
  - Sensitivity to low m_V provided by π, K decays. [E949]
  - Need to use J/ψ, $\Upsilon(1S)$ decays for higher masses of m_V. [BESII'08, BaBar'09, Fayet'09]

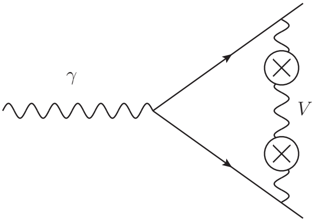
Dark Force Parameter Space



[1] E787. Atiya'92
[2] CDF. Shoemaker'12 [arXiv:1112.5457 [hep-ph]]
[3] KLOE, APEX, MAMI, BaBar. Hewett'12 [arXiv:1205.2671 [hep-ex]]
[4] BES. Ablikim'08 [arXiv:0710.0039 [hep-ex]]
[5] E821. Pospelov'08, [arXiv:0811.1030 [hep-ph]]
[6] Bouchendira'10, [arXiv 1012.3627 [physics.atom-ph]], Gabrielsi'10, [arXiv:1009.4831 [physics.atom-ph]], Aoyama'12, [arXiv:1205.5368 [hep-ph]], Endo'12, [arXiv:1209.2558 [hep-ph]].
[7] E949. Artamov'08, [arXiv:0808.2459 [hep-ex]]
[8] LEP. Hook'10 [arXiv:1006.0973 [hep-ph]]
[9] BaBar. Aubert'08 [arXiv:0808.0017 [hep-ex]], Izaguire'13 [arXiv:1307.6554 [hep-ph]], Essig'13 [to appear]

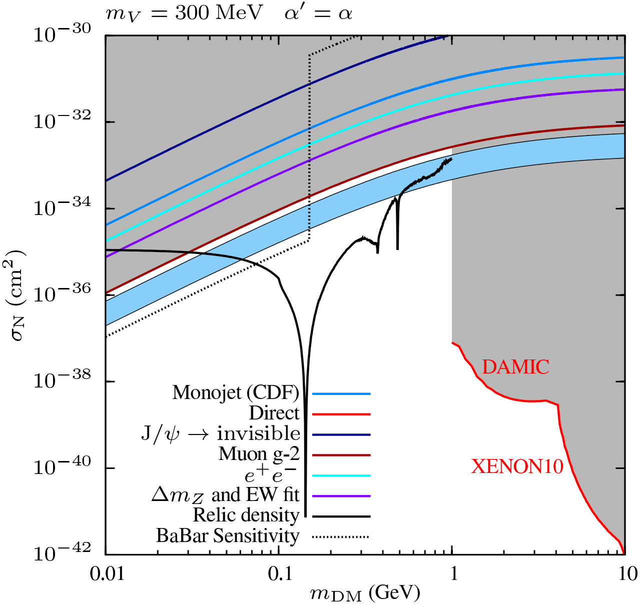
Effect on g-2





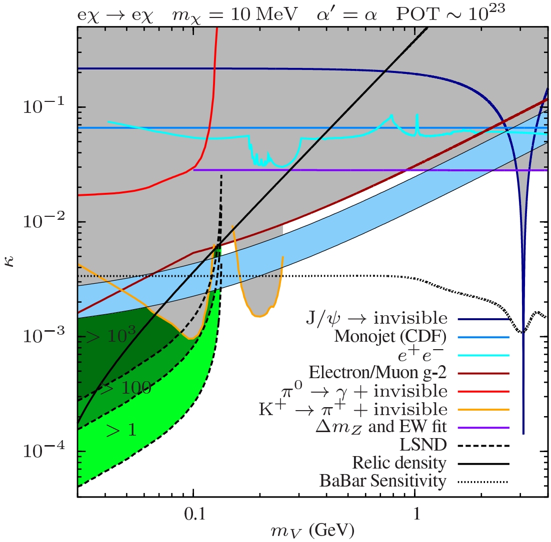
- New 1-loop diagram with inserted V contributes to g-2.
- For the coloured band through the parameter space, the agreement between theory and experiment is improved. [Pospelov '08]

Direct Detection Parameter Space



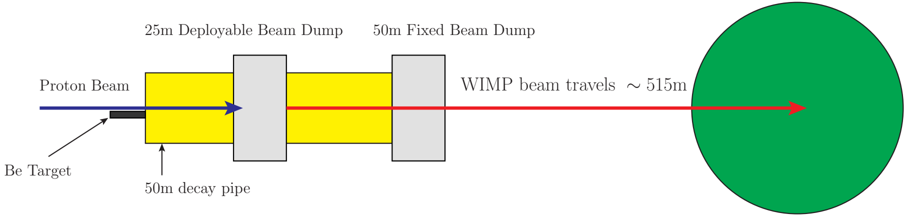
- Increasing m_V shifts all the non-direct detection limits downward, as $\sigma_N \propto \frac{1}{m_V^4}$.
- CRESST-I provides slightly weaker bounds than DAMIC in the very low mass region.
- XENON100 provides the best limits for $m_\chi > 9$ GeV.

LSND



eχ → eχ $m_\chi = 10$ MeV $\alpha' = \alpha$ POT ∼ 10^{23}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
κ
0.1
1
m_V (GeV)
> 10^3
> 100
> 1
J/ψ → invisible
Monojet (CDF)
e^+e^-
Electron/Muon g-2
$\pi^0 \to \gamma$ + invisible
$K^+ \to \pi^+$ + invisible
Δm_Z and EW fit
LSND
Relic density
BaBar Sensitivity

MiniBooNE Proposal



- Can direct the proton beam around the target and into the 50m absorber to reduced neutrino signal by factor of ~ 40.
  - Optionally, could also deploy a 25m absorber to reduced backgrounds by a factor of ~ 80.
- MiniBooNE has a timing resolution of $\sim 1.8\mathrm{ns}$. Can impose a timing cut of 3 ns to remove 90% of the neutrino signal.
  - Can increase cut to 6 ns to remove 99.9% of neutrino signal.
  - Does reduce sensitivity to lower dark matter masses.

[arXiv:1211.2258v1, with Richard Van de Water]